Modeling xenon and argon physics with the Noble Element Simulation Technique (NEST)

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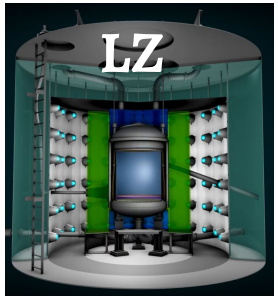
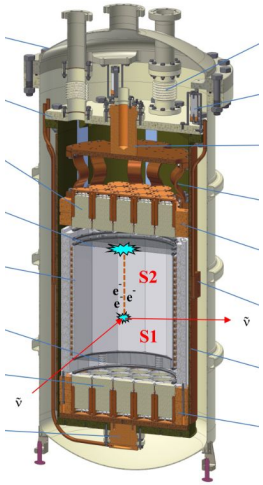
NEST

The Landscape of Noble Liquids for Particle Detection

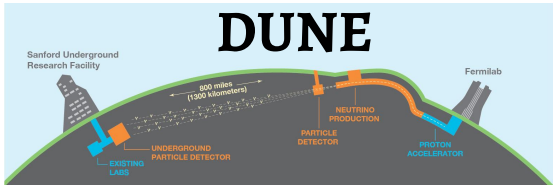
"Detectors using noble elements as the detection medium, such as liquid and gaseous argon and xenon, have risen to become a prime technology for the following Science Drivers: **1)** Pursue the physics associated with neutrino mass; **2)** Identify the new physics of dark matter; **3)** Explore the unknown: new particles, interactions and physical principles"
Basic Research Needs for High Energy Physics Detector Research & Development

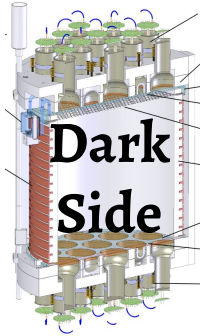


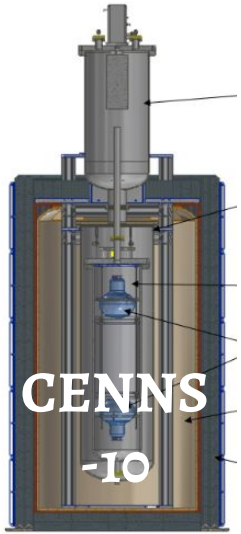
XENONnT



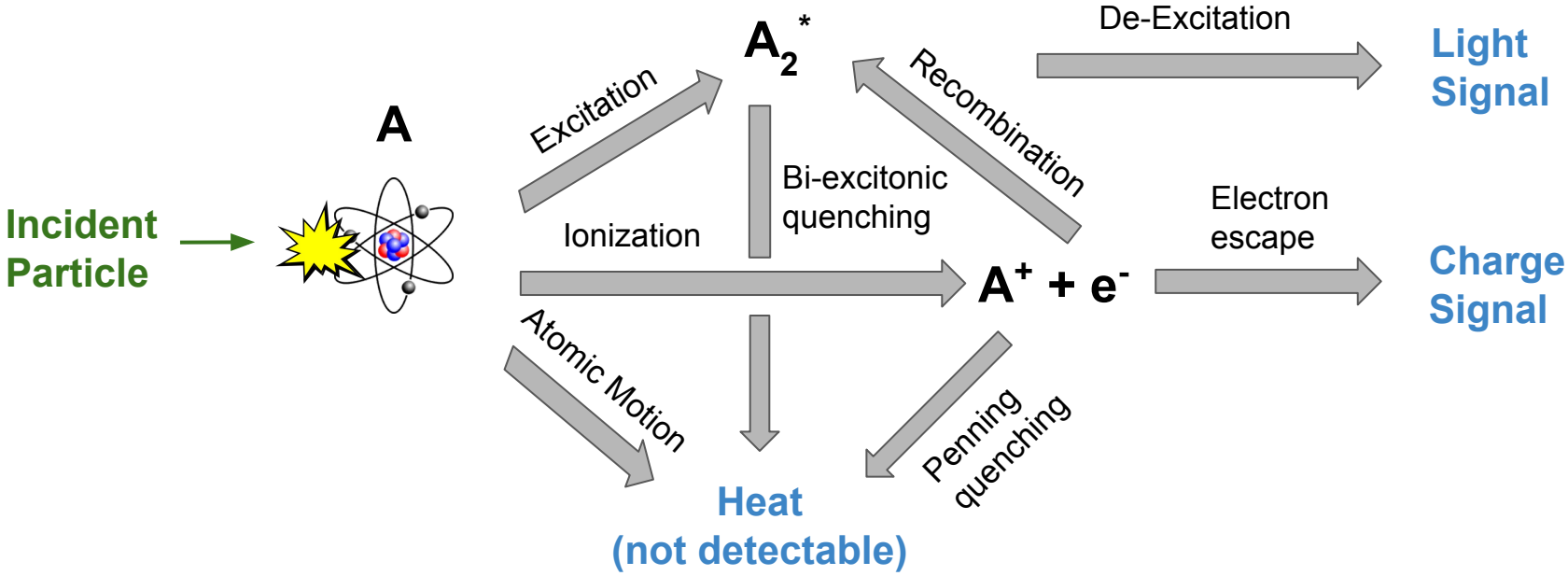
RED-100



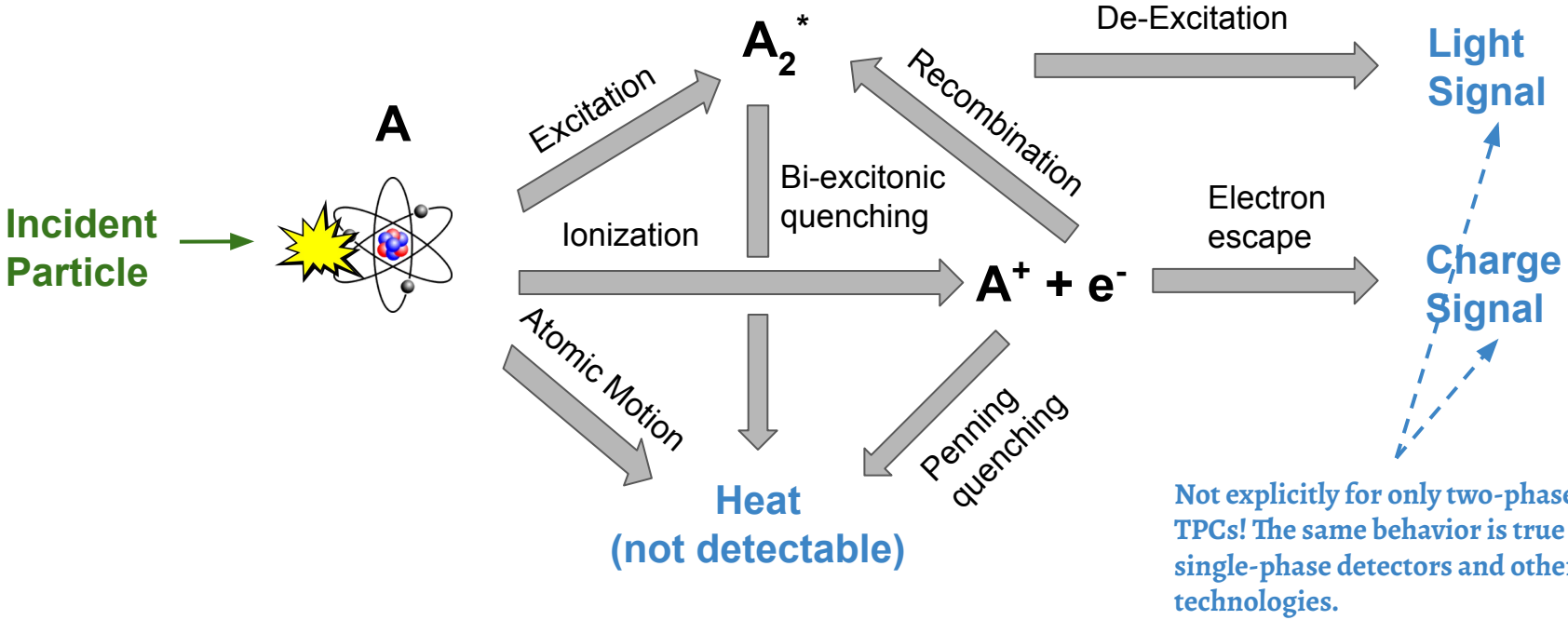




How is Energy Deposited?



How is Energy Deposited?

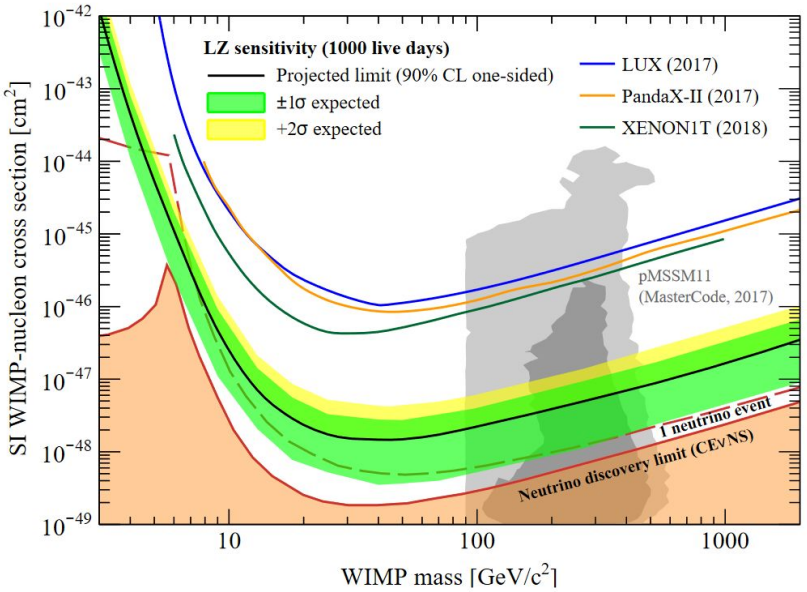


What is NEST?

- Inter-collaboration collaboration
  - Members from LUX, LZ, XENON, (n)EXO, RED100, COHERENT, DUNE, ICARUS, MicroBooNE, SBN
- We provide models of energy deposition, as well as code to implement this in an actual detector
  - https://github.com/NESTCollaboration
- Primary code is in C++, and bindings are available to easily use NEST in Python
- Xenon models are the most mature, but accurate argon models are available!
- Integration with ROOT and Geant4
- Collaboration website: http://nest.physics.ucdavis.edu/

Who uses NEST?

- Lots of people!
- NEST publications and code have been cited by 200 journal articles, and an additional 50+ theses and conference proceedings
  - Dark matter limits and projections
  - Physics searches
  - Detector calibrations
  - Theoretical models
- Snowmass Letter of Interest was signed by 140+ authors across 4 continents, including experimentalists and theorists

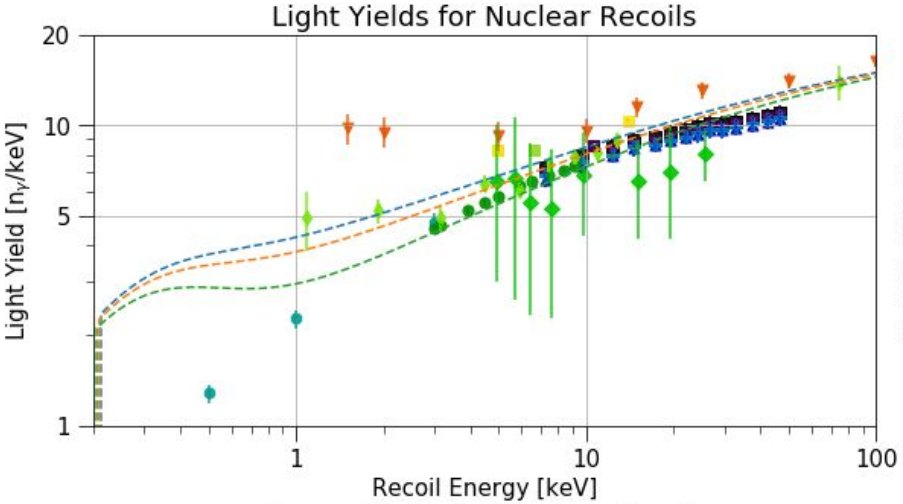


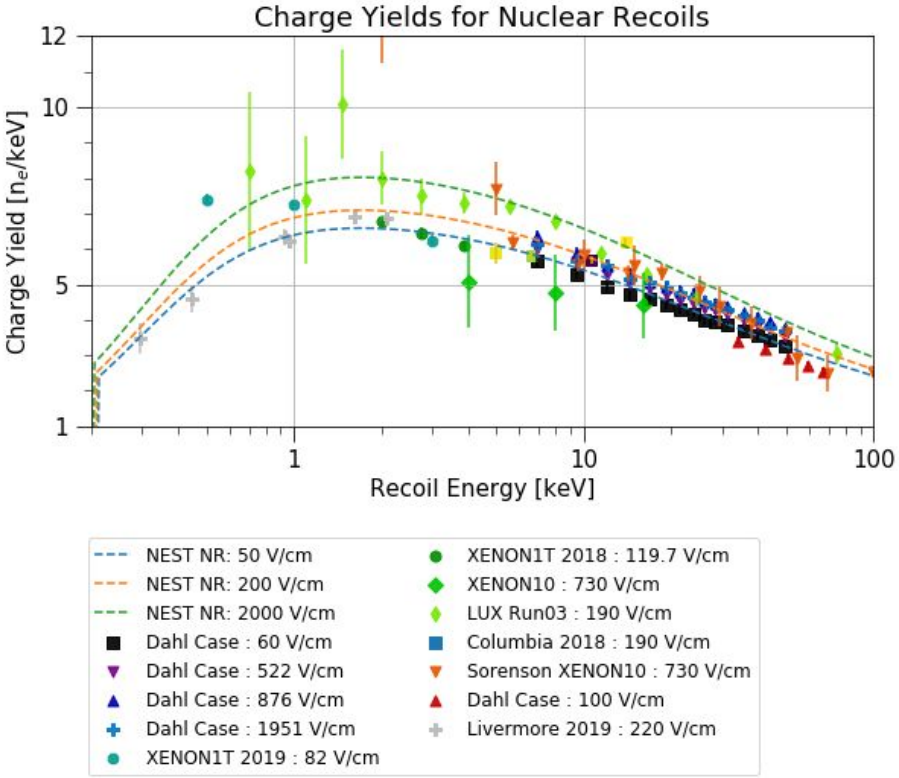
Modeling Atomic and Nuclear Physics of Xenon

- NEST models are semi-empirical: built as averages of world data, incorporating physically-motivated models when feasible
  - Data as far back as 1970s (Kubota)
- Models for various types of energy deposits: electronic recoils, nuclear recoils, alphas, etc.
- Calculate average light yield, charge yield, recombination → simulate actual energy deposits in a detector

Nuclear Recoils in Xenon

Models the light and charge signals, as well as the amount of energy lost to heat

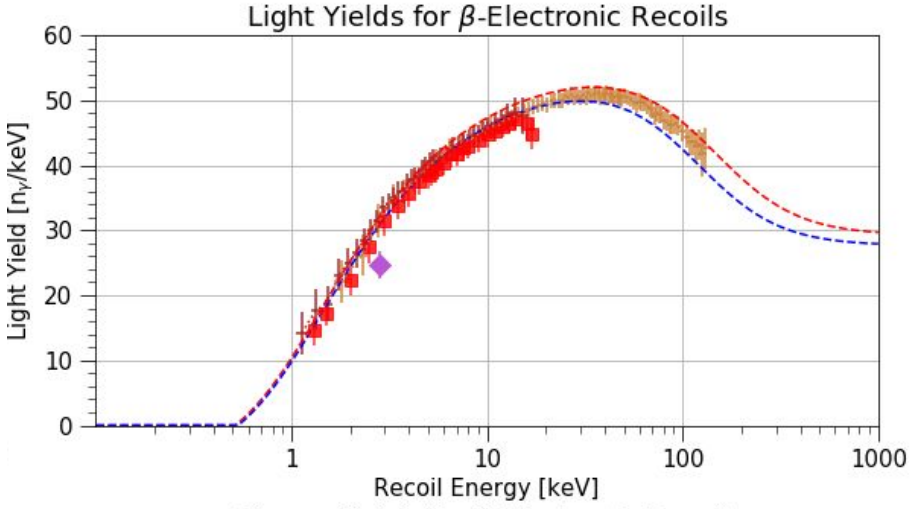


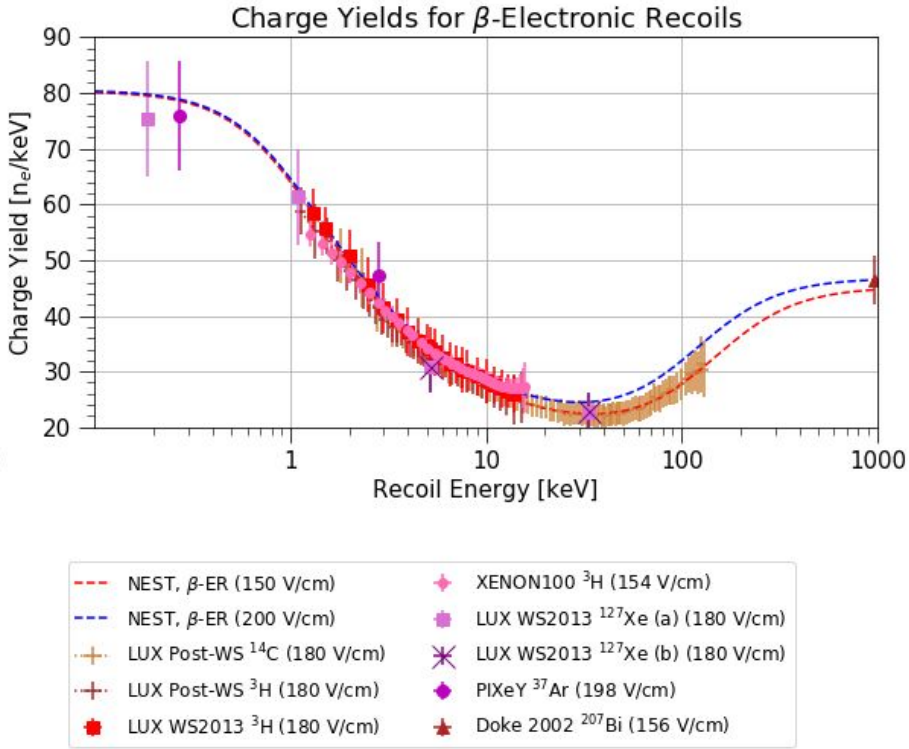


Electronic Recoils in Xenon

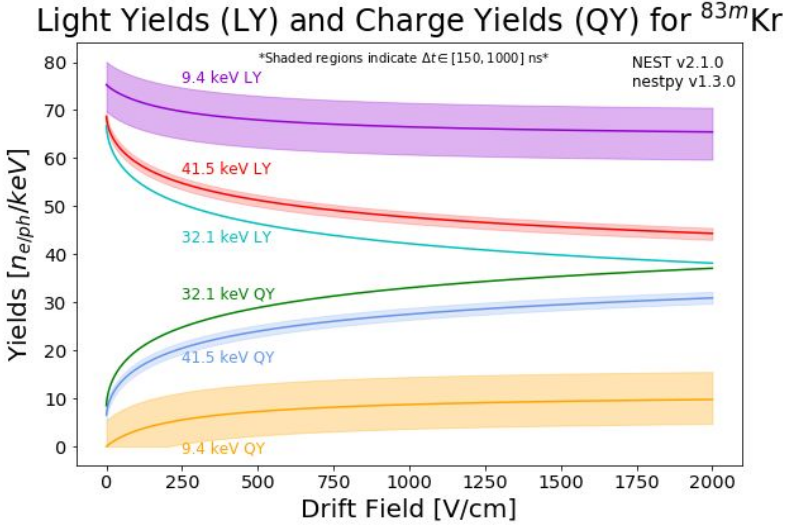
Two models for ERs: “beta” and “gamma”

“Beta” model at 150-200 V/cm is shown in these plots





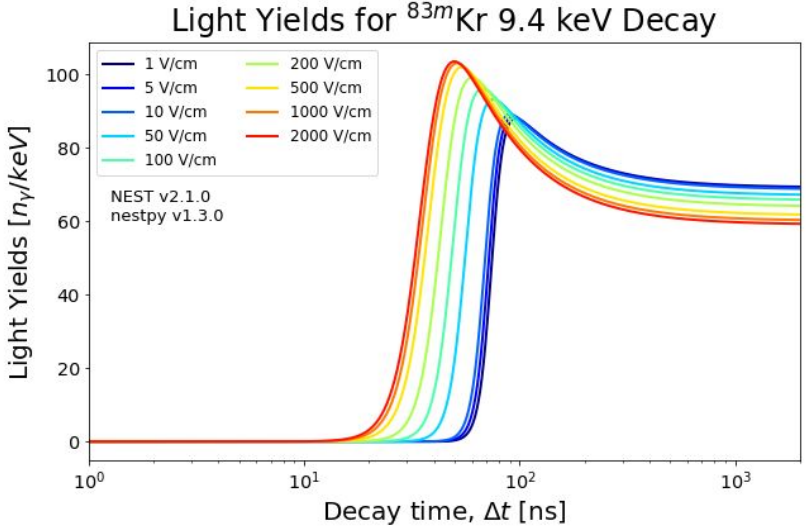
^{83m}Kr in Xenon



Common calibration source in xenon detectors

Model compares well to data from PIXeY, Xurich, LUX, PANDA-X

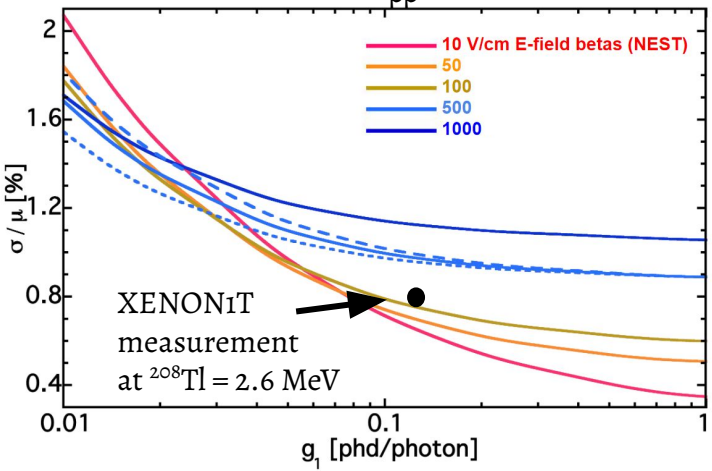
Two-step conversion electron process, depositing 32.1 and 9.4 keV. The second deposition depends on the time between the decays, exponentially distributed with $t_{1/2} = 150$ ns.



Energy Resolution in Xenon

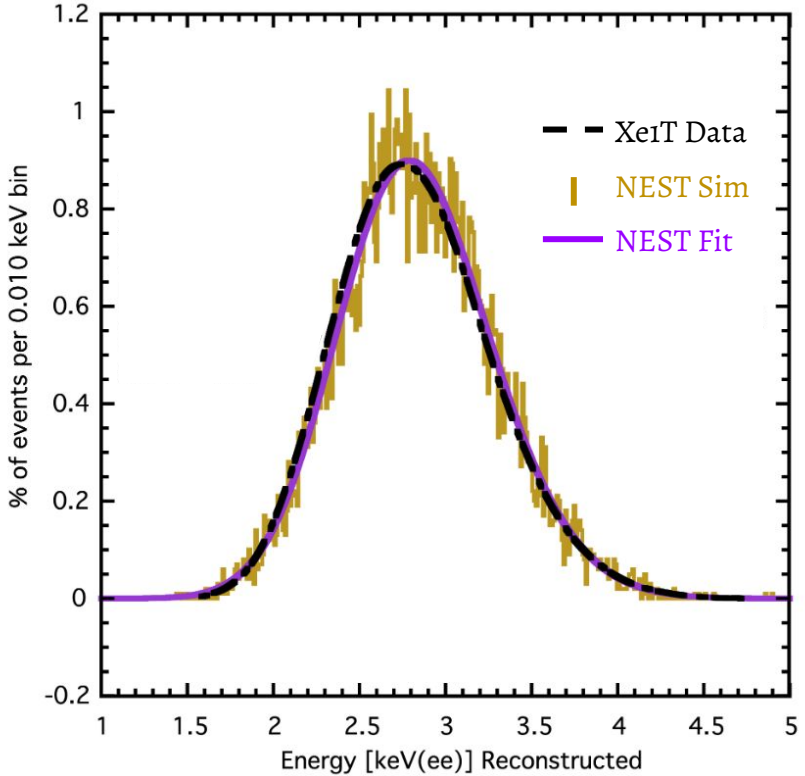
$$E = W_{Xe}\, n_q = W_{Xe}\,(S1 / g1 + S2 / g2)$$

High Energy: $Q_{\beta\beta} = 2.5$ MeV



arXiv:2102.10209
(Comprehensive analysis on energy reconstruction)

Low Energy: ^{37}Ar Peak

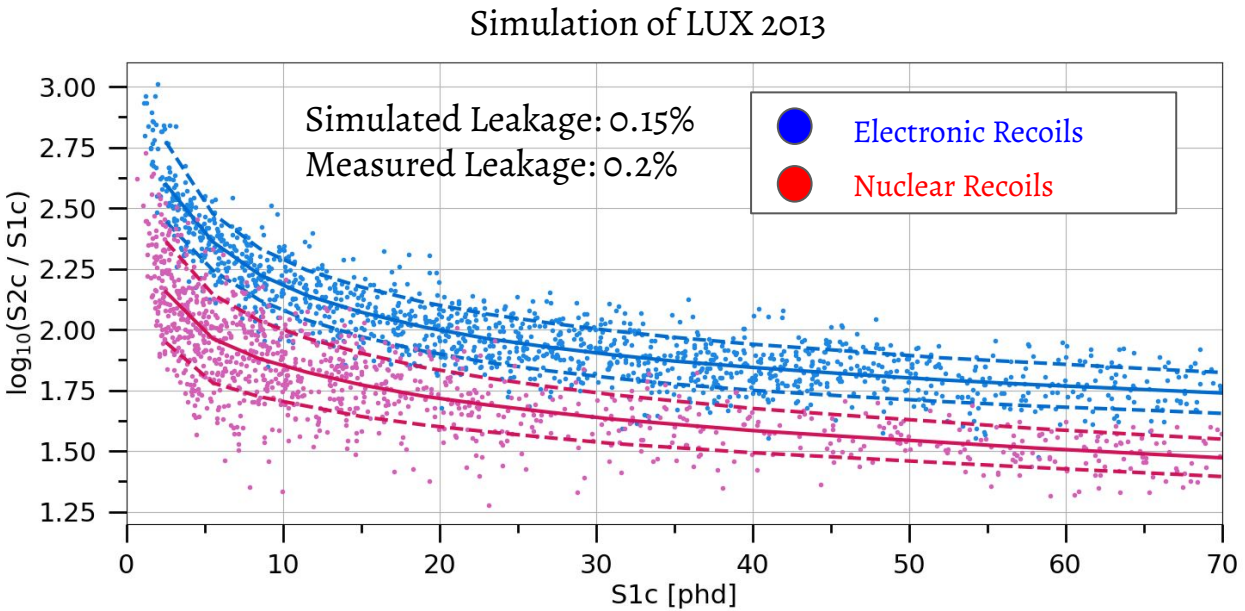


arxiv:2007.00528

Discrimination in Xenon

Discriminate electronic vs. nuclear recoils by using the charge-to-light ratio

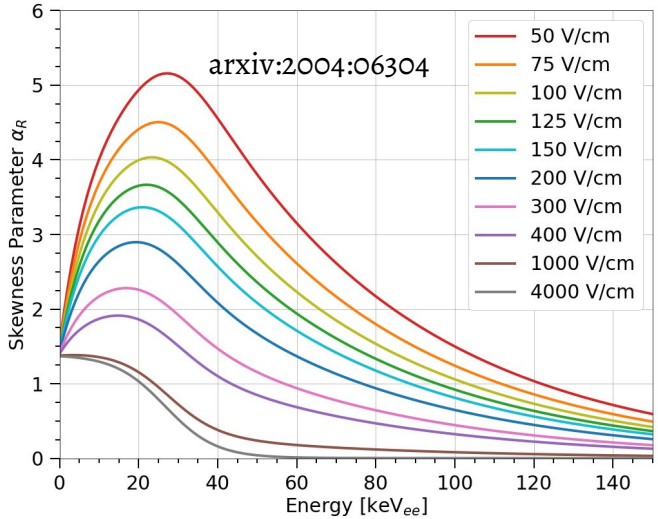
(Other possibilities present, e.g. pulse shape)

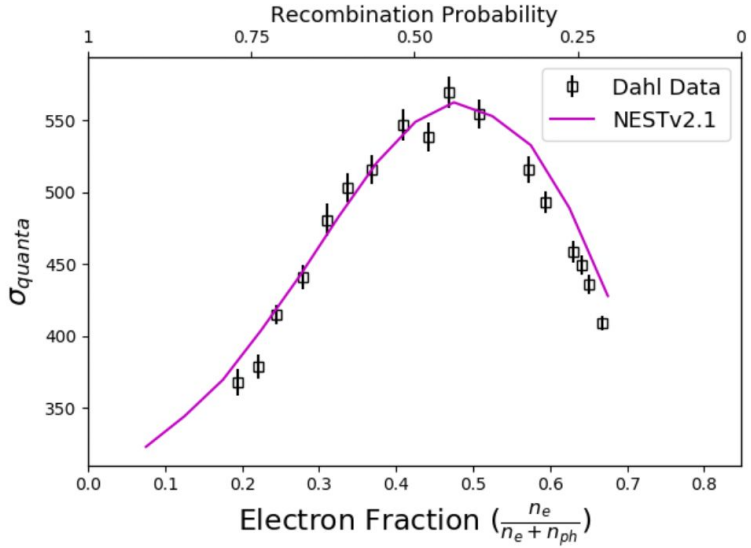


Recombination Physics in Xenon

Fluctuation in electron-ion recombination is the largest obstacle to ER/NR discrimination.

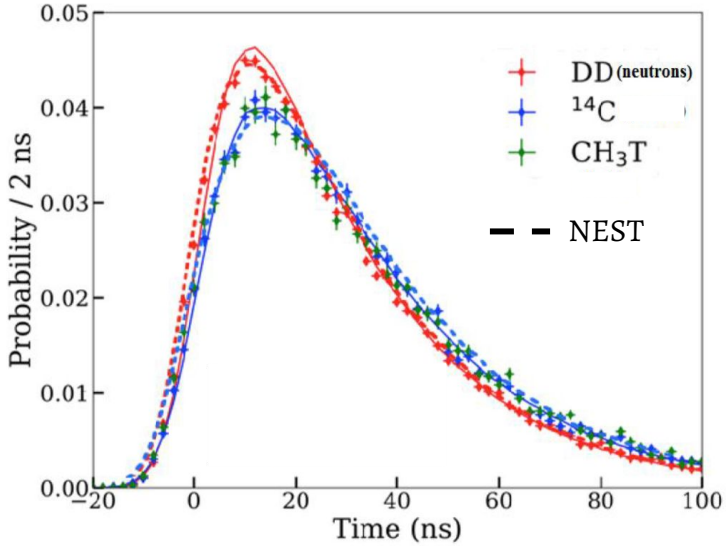
NEST models these using lessons from data: these fluctuations are super-binominal and skewed.

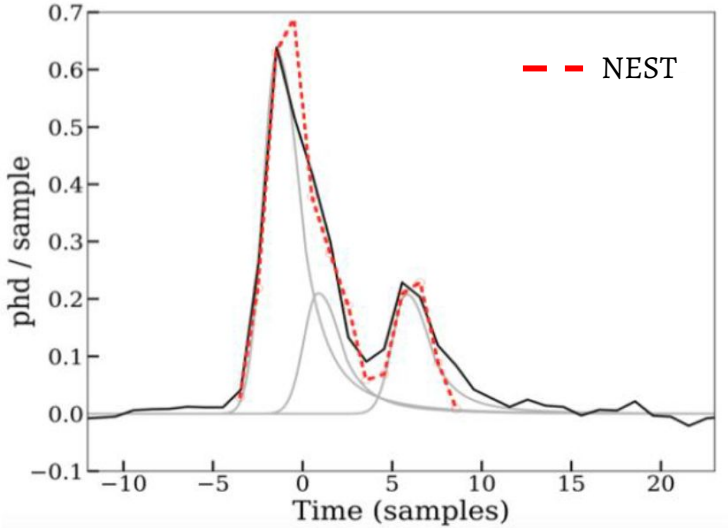




Pulse Shape in Xenon

NEST can simulate S1 and S2 (and single electron) pulse shapes in liquid xenon, e.g. to use in raw data generation. Below: NEST simulations, overlapped with LUX measurements.





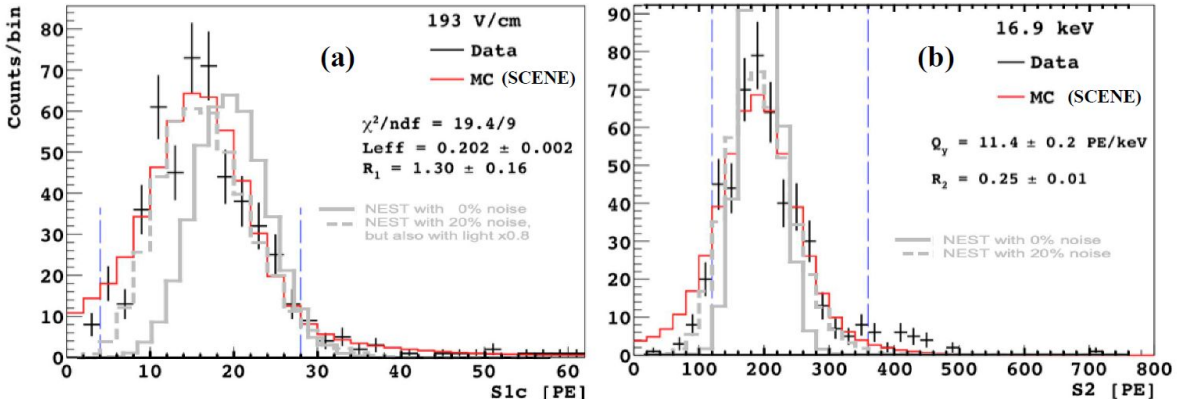
LUX measurements from arXiv:1802.06162

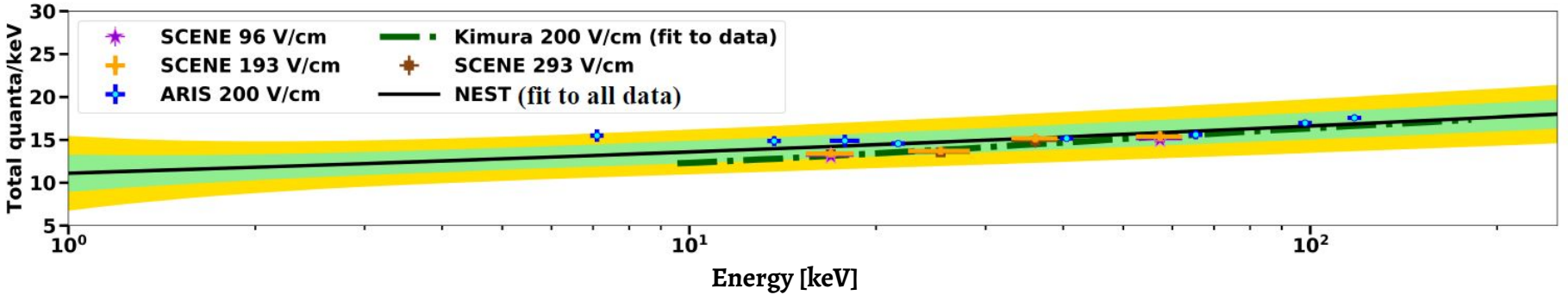
Nuclear Recoils in Argon

arXiv:2102.10209

Nuclear recoil argon model now deployed in main NEST code

Built using data from SCENE, ARIS, DS-50, Joshi, Aprile, Lippincott, Kimura, Doke, etc.

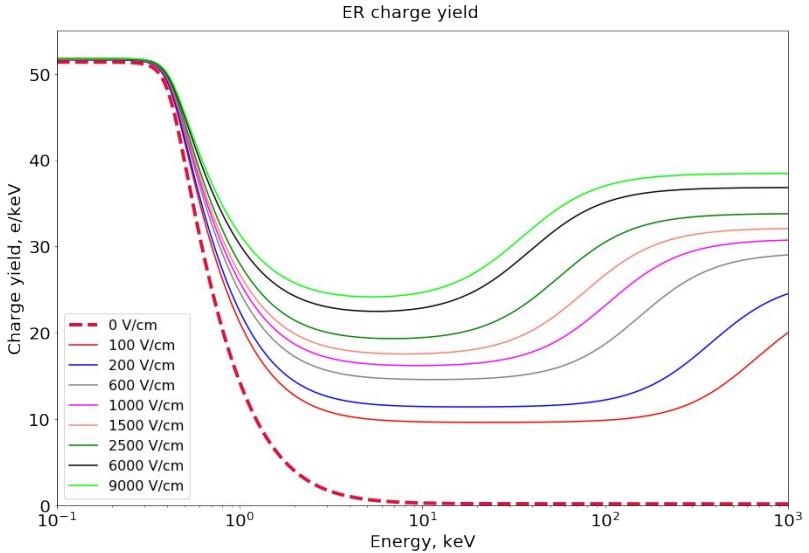


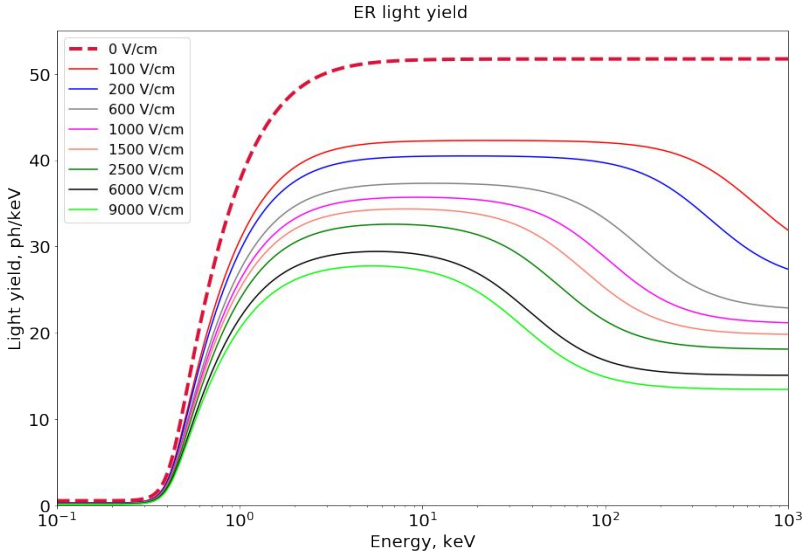


Electronic Recoils in Argon

Electronic recoil model also published in NEST code, based on world data

Disclaimer: this model is still in the progress of being finalized, subject to change



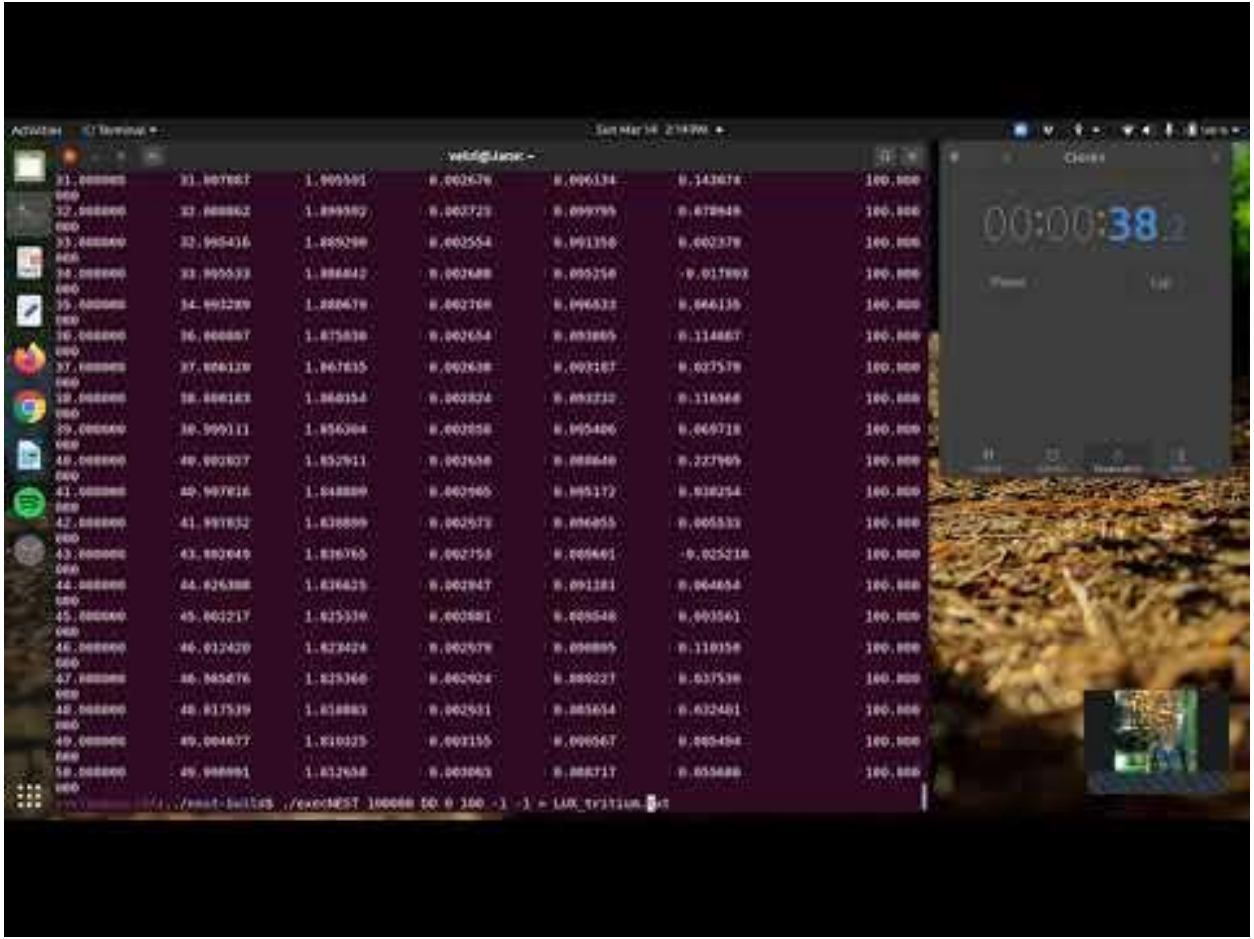


“How can I use NEST?”

- I’m glad you asked!
- NEST is packaged with a variety of tools for you and your collaboration
  - C++ libraries to implement in your framework and/or GEANT4
  - Python bindings to the C++ code, to use in your existing Python analysis framework
  - Limited system requirements for most usages
  - Examples + tutorials
    - execNEST, rootNEST, bareNEST in C++
    - Nestpy tutorial (really excellent notebook!): http://bit.ly/nestpy
  - Documentation: analysis notes available at http://nest.physics.ucdavis.edu/
  - Want to request a new functionality? You can do so via Github: https://github.com/NESTCollaboration/

Demonstration of NEST

[Note: if viewing a PDF document, click on the image to access the demo video on Youtube]



Closing Remarks

- NEST is directly tied to Priority Research Direction 6: "*Improve the understanding of detector microphysics and characterization*"
  - But our code and models are applicable to many PRDs, TRs, Science Drivers
  - E.g. "*Manipulate detector media to enhance physics reach*", "*Addressing challenges in scaling technologies*"
  - Fundamentally, NEST is a one-stop shop to answer most questions about designing your detector and doing data analysis
- NEST is stable enough to be reliable, while also evolving to incorporate new data and features
- Recent + upcoming changes: improvements to LAr ER model, LXe ER model, gamma calibrations, W-value, noise

NEST Collaboration Members